# AFRL-ML-TY-TP-2005-4508


# Full Scale Testing of Polymer Reinforced Blast Resistant Windows

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**Interim Report, December 2004**



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14. ABSTRACT

**Summary of the state of the art in research and design of protective glazing and recent full-scale testing efforts of the Air Force Research Laboratory (AFRL) on blast resistant windows that use advanced materials. Failure mechanisms observed from recent explosive tests are presented, along with analytical models that are being developed to predict the resistance provided by the polymer reinforcement. Challenges include optimizing mechanical properties of reinforcement, design thickness and lay-up of the polymer and glass layers, and designing optimum mechanisms for transferring load to host structure. The needs and direction of future blast resistant window research are discussed.**

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# *Full Scale Testing of Polymer Reinforced Blast Resistant Windows*

***December 2004***


**Elizabeth Trawinski, 1st Lt, USAF**
**U.S. Air Force Research Laboratory**
**Materials and Manufacturing Directorate**
**Airbase Technologies Division**
**Force Protection Branch**
**Tyndall AFB, Florida**

# Topics of Discussion

- Current design of blast resistant windows
- Development of AFRL blast resistant windows
- Design approach
- Full-scale experiments
- Material testing
- Modeling
- Future goals

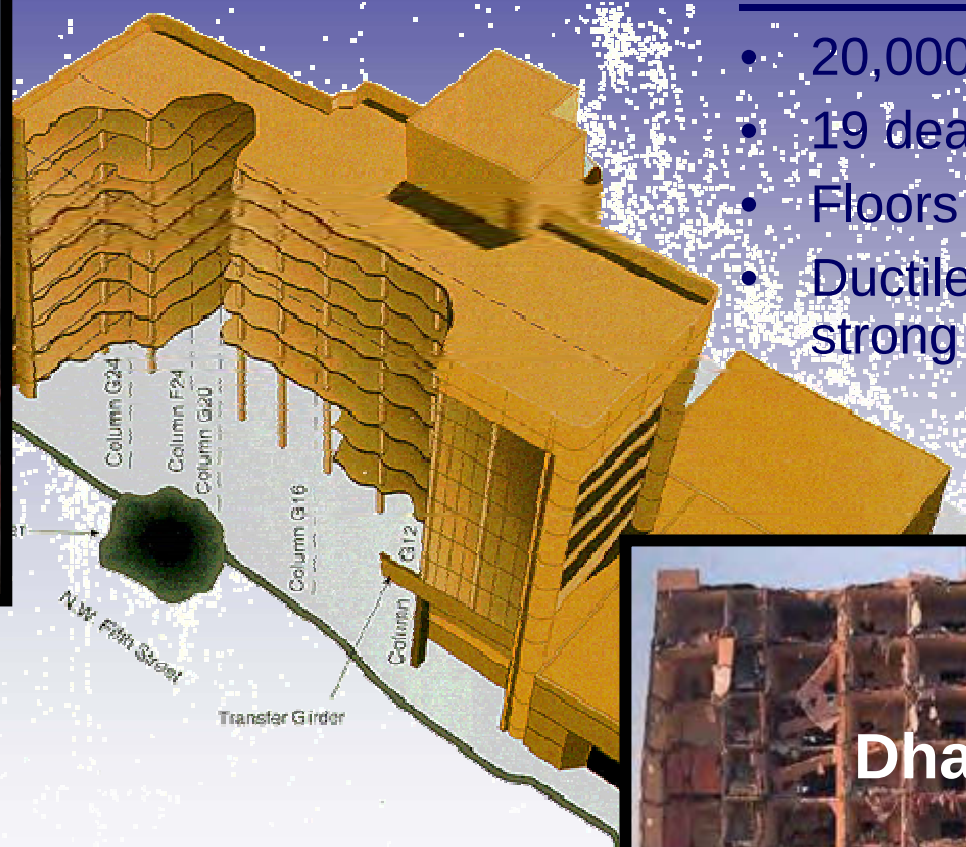
# Current Design of Blast Resistant Windows

- High profile targets
  - Airports / highly populated areas
  - Embassies
  - Government facilities

# High Profile Targets


## Murrah Building

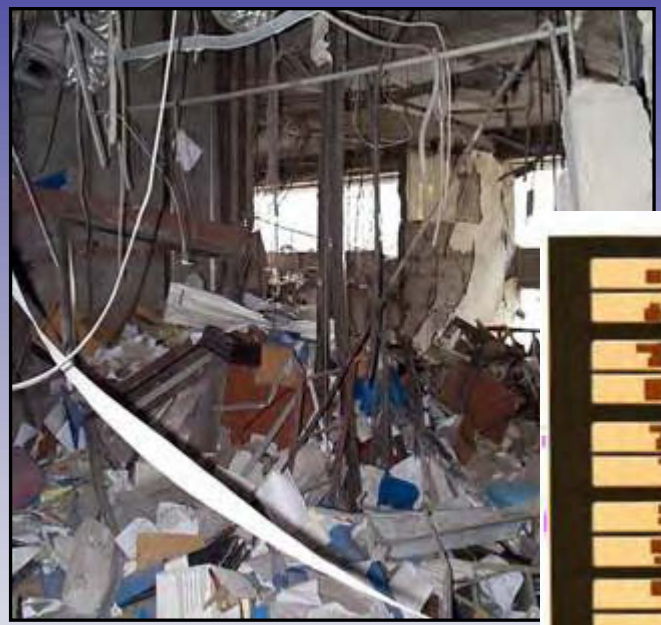
- 4,000-lb bomb
- 168 deaths
- Floors progressively collapsed
- Beam and column discontinuity

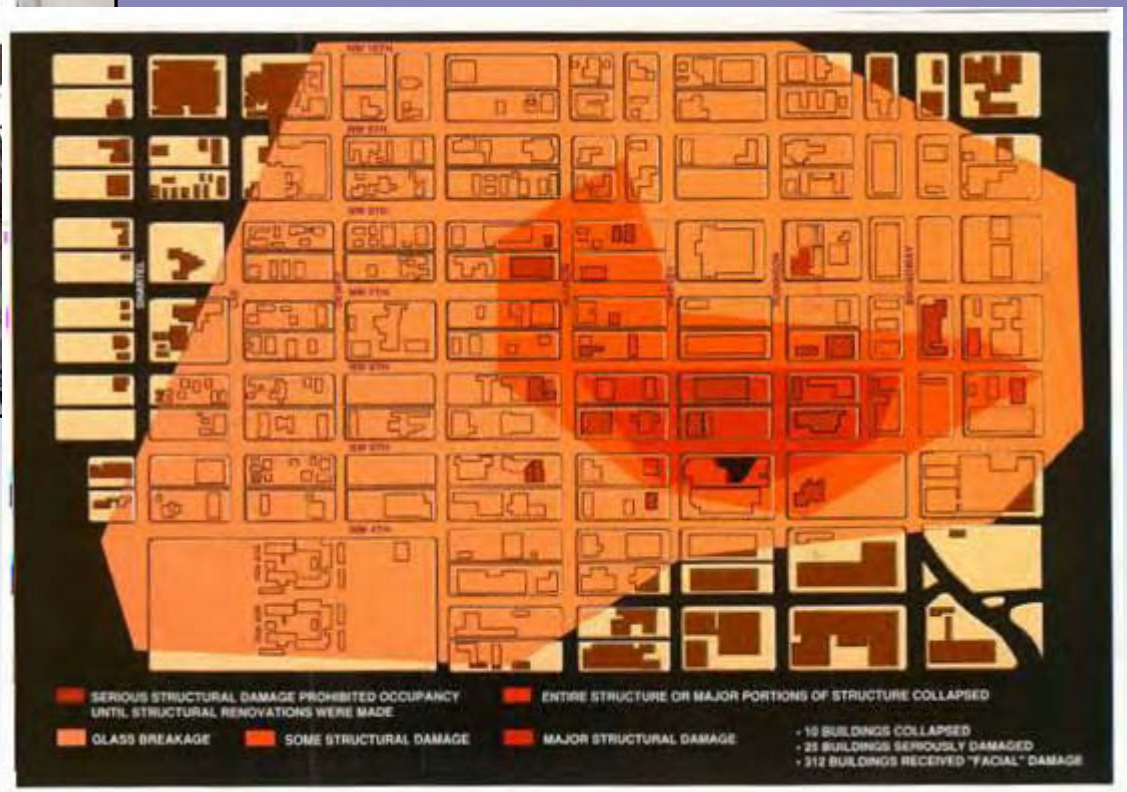



## Khobar Towers

- 20,000-lb bomb
- 19 deaths
- Floors did not collapse
- Ductile structure with strong joints

# High Profile Targets



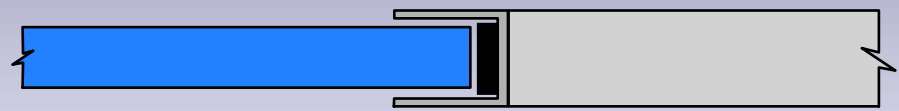


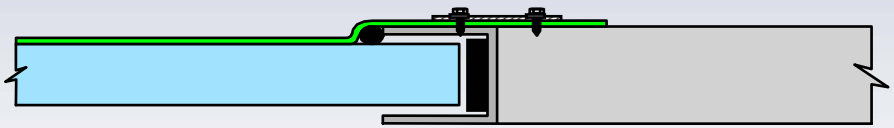

Glass Hazards
> 80% Human
Casualties

# Current Design of Blast Resistant Windows

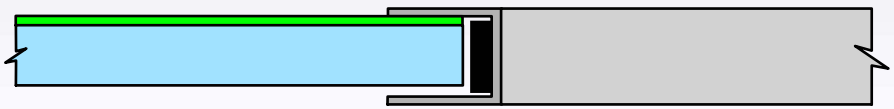
- High profile targets
  - Airports / highly populated areas
  - Embassies
  - Government facilities

- Design methods
  - Large bites with thick glass
  - High strength anchored films



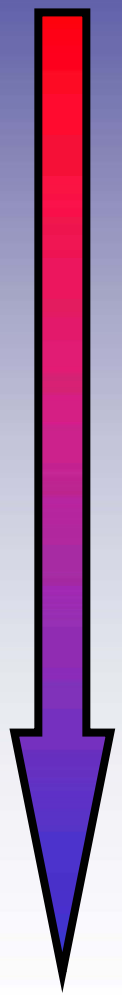


**Film captured externally**



**Film captured in the bite**

# Design Methods - Glazing Options



- **Annealed Glass** Fails at ~0.2 psi into shards
- **Chemically Treated Glass** Reacts like annealed glass
- **Wire-Reinforced Glass** Reacts similar to annealed glass
- **Acrylic (Plexiglass)** Fails similar to annealed glass
- **Heat Strengthened Glass** Fails at ~0.4 psi into shards
- **Fragment Retention Film** Film (4 mil+) holds fragments; blunt trauma hazard unless film retained by frame/catcher system
- **Thermally Tempered Glass** 4-5X stronger than annealed glass; fractures into small cubes
- **Laminated** Use interlayer bonding materials with plies of glass, polycarbonate or both; frame can be weak point
- **Polycarbonate** Suitable for blast resistance up to ~5 psi; can abrade and degrade from UV unless coated

# Design Methods - Glazing Options (Videos)

Annealed/Heat Strengthened

Film Glazing

Anchored Film Glazing

# Current Design of Blast Resistant Windows

- High profile targets
  - Airports / highly populated areas
  - Embassies
  - Government facilities
- Design methods
  - Large bites with thick glass
  - High strength anchored films
- Design examples…

# Design Examples - Fragment Retention Film

- Broken, annealed glass turns into shards
- Fragment retention film (e.g., “Mylar”) holds shards together
  - Minimum 4 mils thick
  - Glass/film bond important
  - Estimated life of ~10 years
- Film with catcher bar provides good level of protection at low cost (Army TL 1110-3-501, 14 Jul 99)

# Design Examples – Stainless Steel Net Blast Curtain

# Design Examples – Arpal Windows

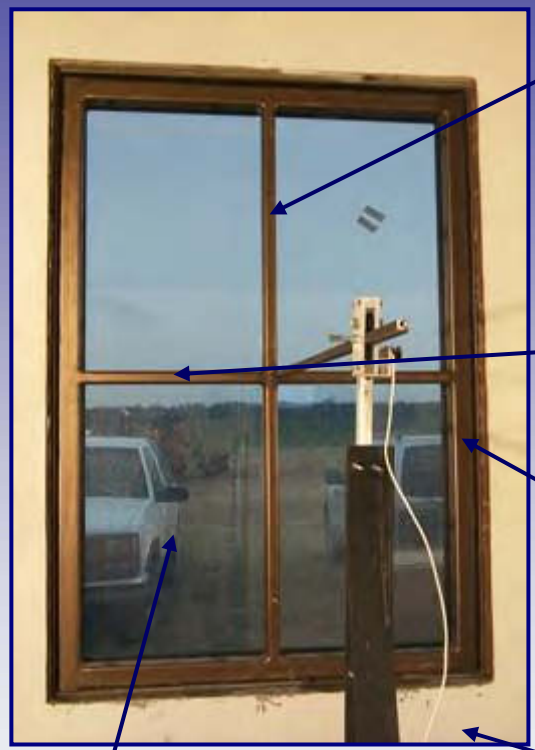
- Window size: 5’2”x7’1”
- Thin glass laminates
- Cables used to absorb energy

- Aluminum shear devices absorb energy
- Complex system
- Very practical windows

# Design Examples - Structural Muntin Windows

Exterior View

Interior View



Vertical Non-continuous Muntin Steel Tubing Member

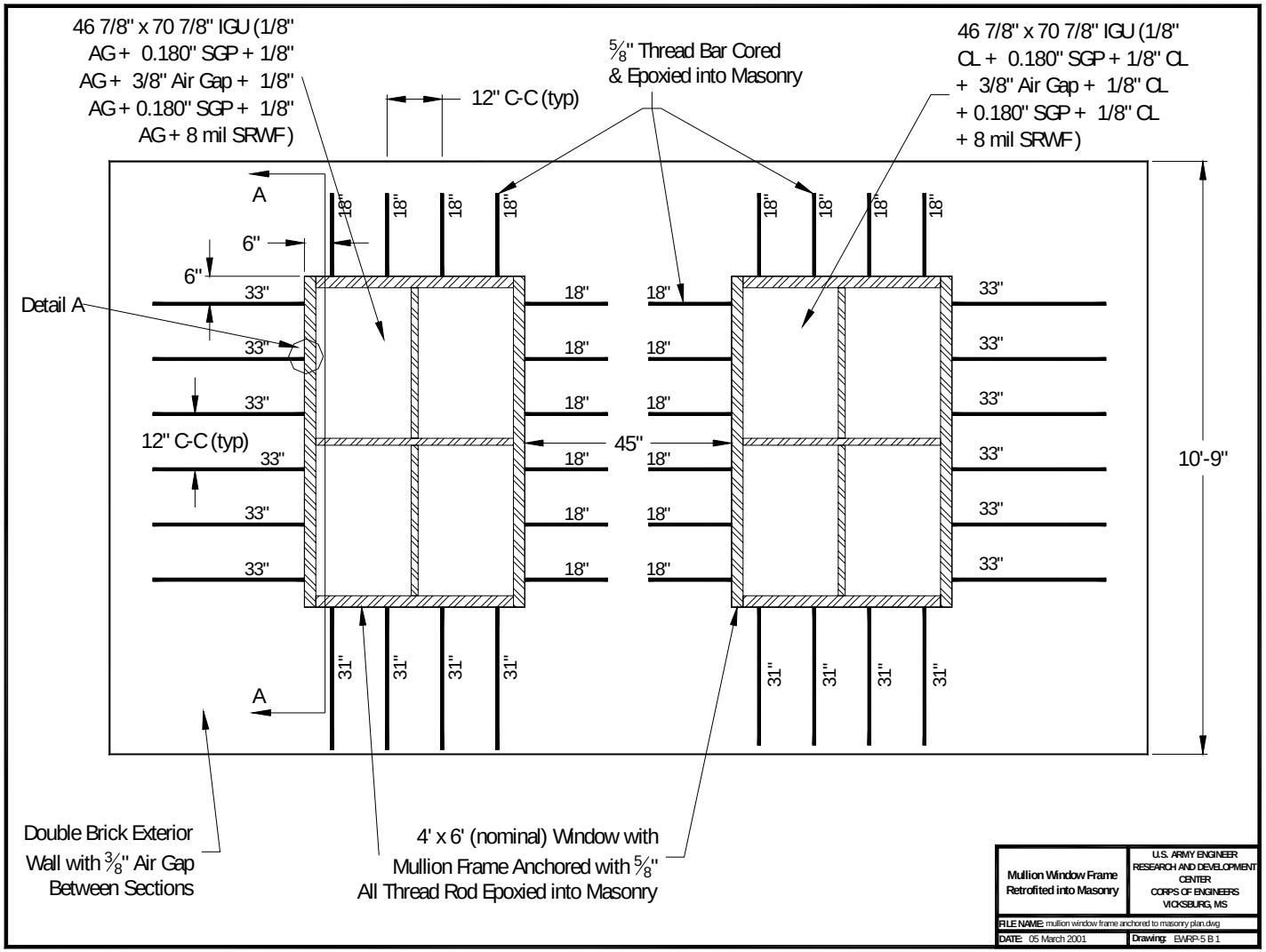
Horizontal Continuous Muntin Steel Tubing Member

Steel Tubing Muntin Window Frame Anchored Into Masonry Wall Using Threaded, Epoxied Rods

Two sandwiched interlayers of 1/8" AG (Annealed Glass) + 0.180" SGP (Sentry Glass Plus) +1/8" AG with 3/8" Air Gap between + 8 mil Shatter Resistant Window Film

Coreguard Consisting of 20 Gage Sheet Metal Glued to ¼" Gypsum Board

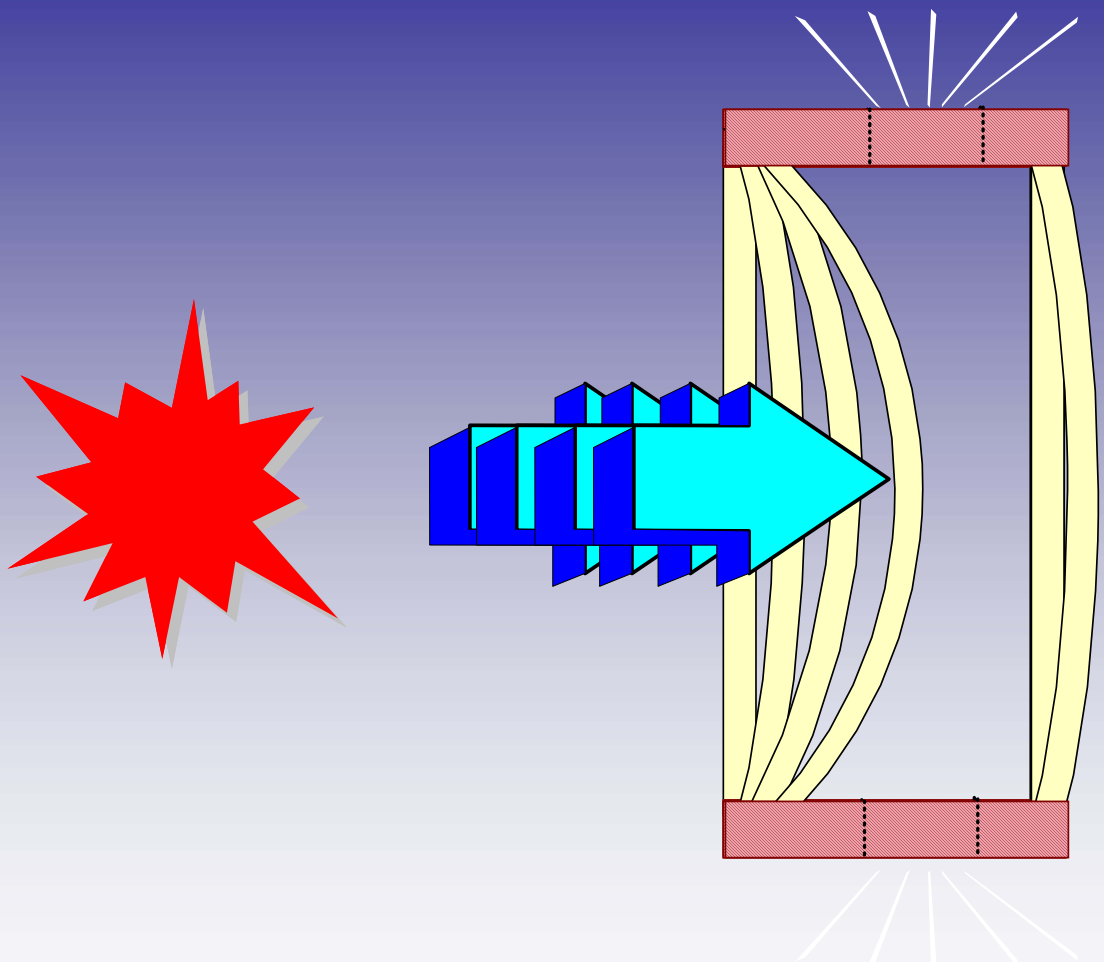
# Design Examples - Structural Muntin Windows



# AFRL Blast Resistant Windows New Concepts

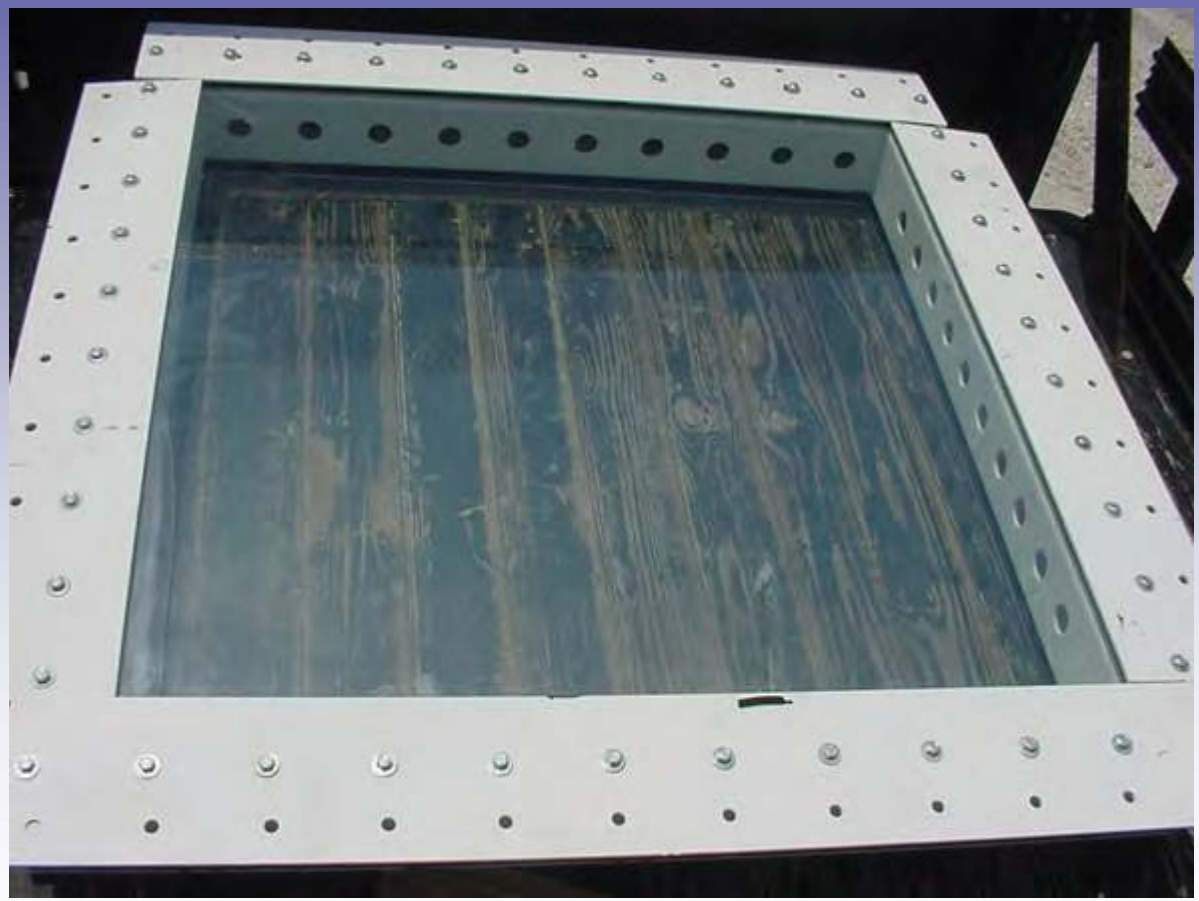
- Damping chamber windows
- Perimeter anchored laminate (PAL) glazings
- Engineered thermoplastics with abrasion resistant coatings

# Damping Chamber Windows

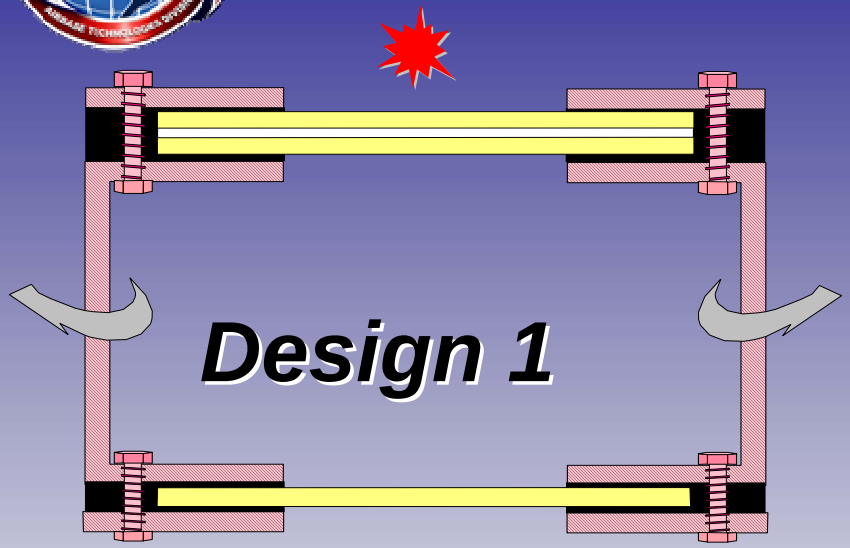


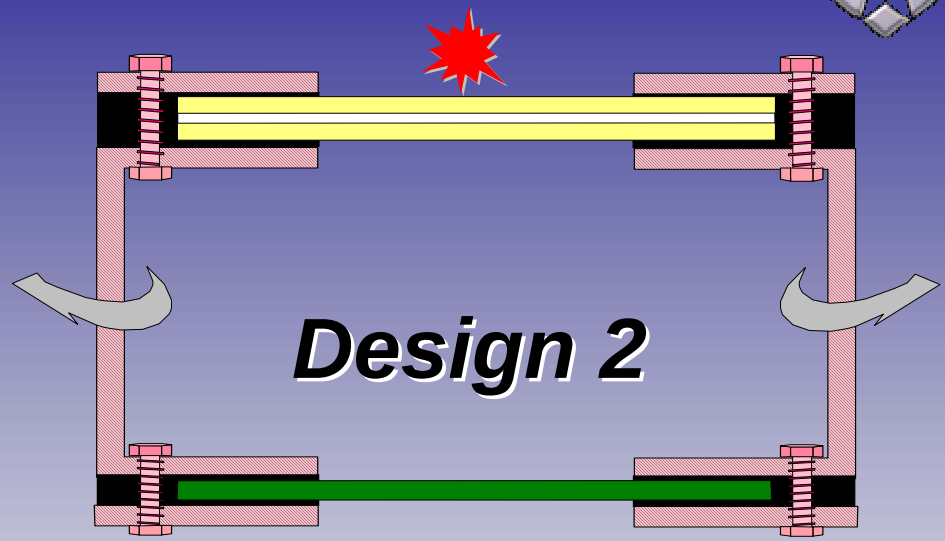

Conceptual Performance of Damping Chamber Window

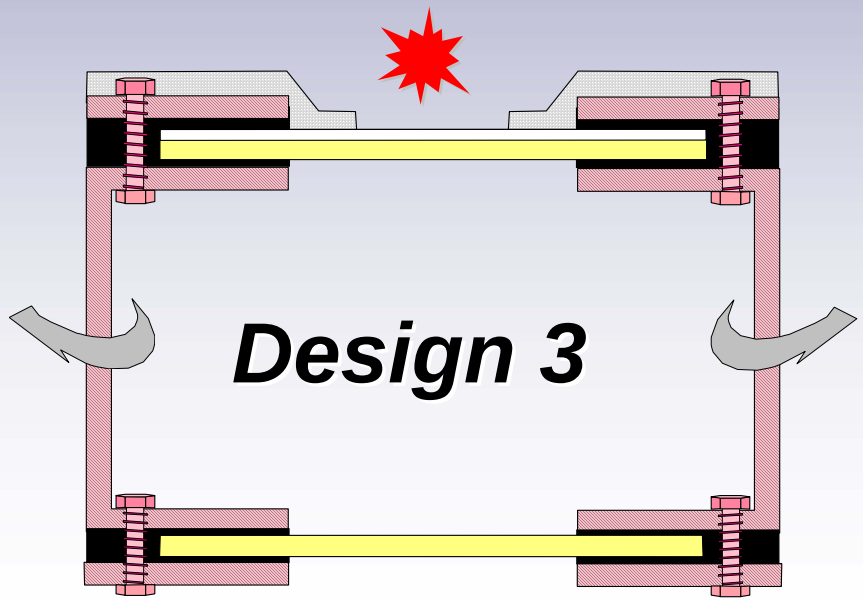
# Damping Chamber Window Window Frame

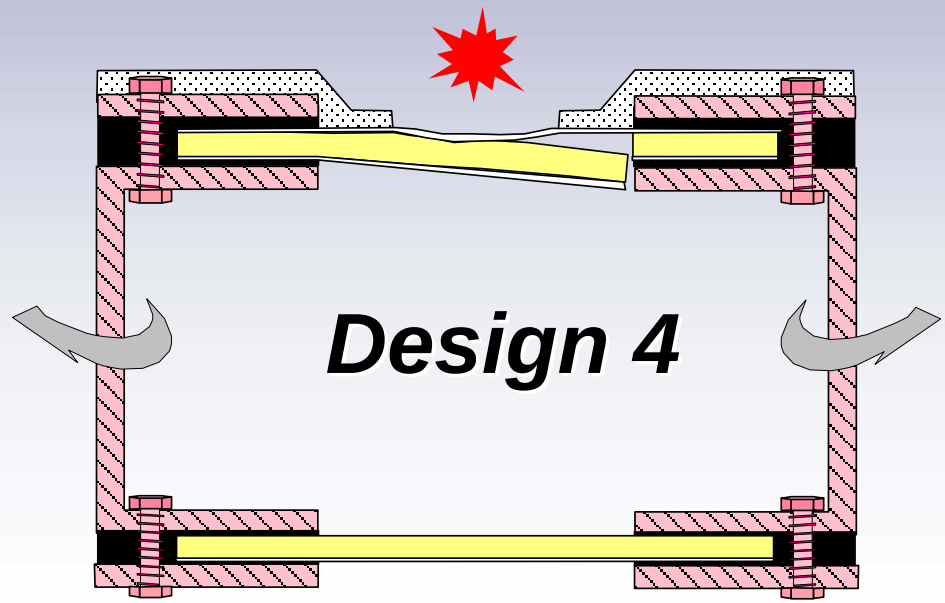


# 1st Generation Windows

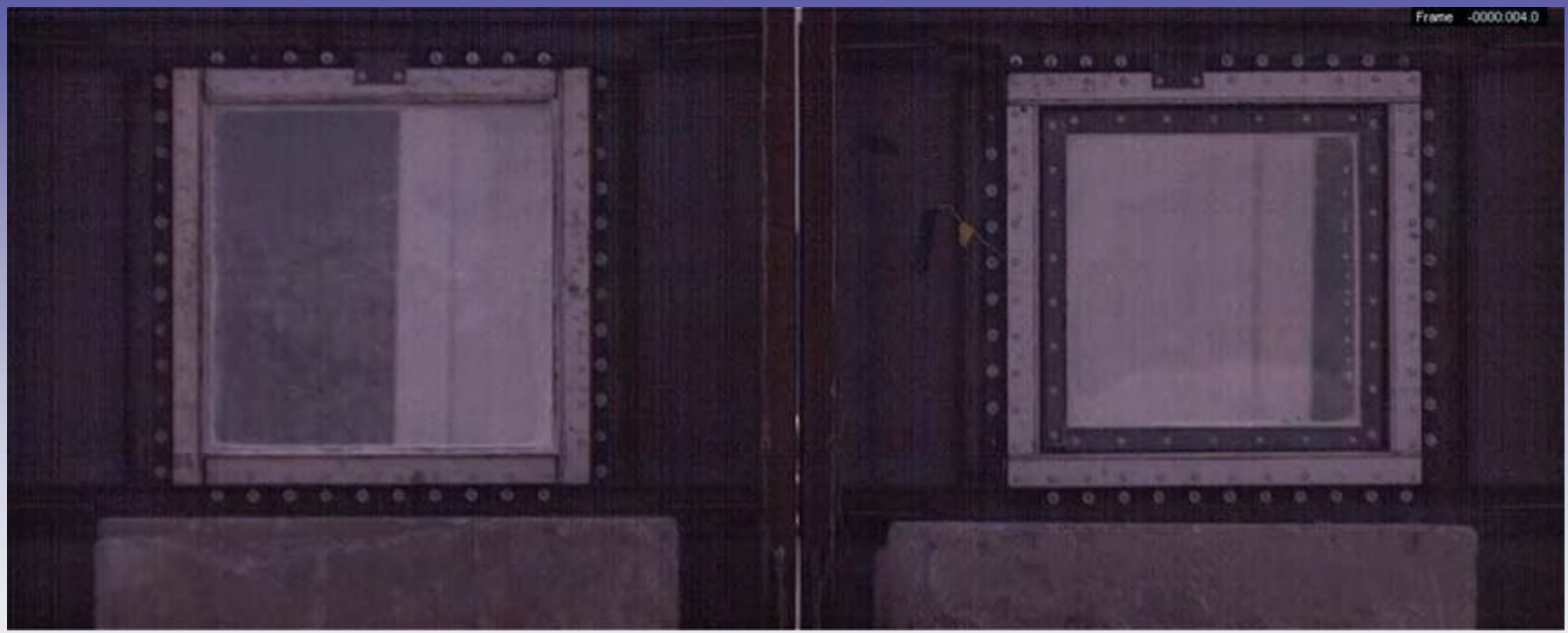


# 2nd Generation Designs 3 and 4




High Speed Video of 2nd Generation Damping Chamber Window Designs 3 and 4 During Testing

# 2nd Generation Design 3

Pretest Photo of Blast Side

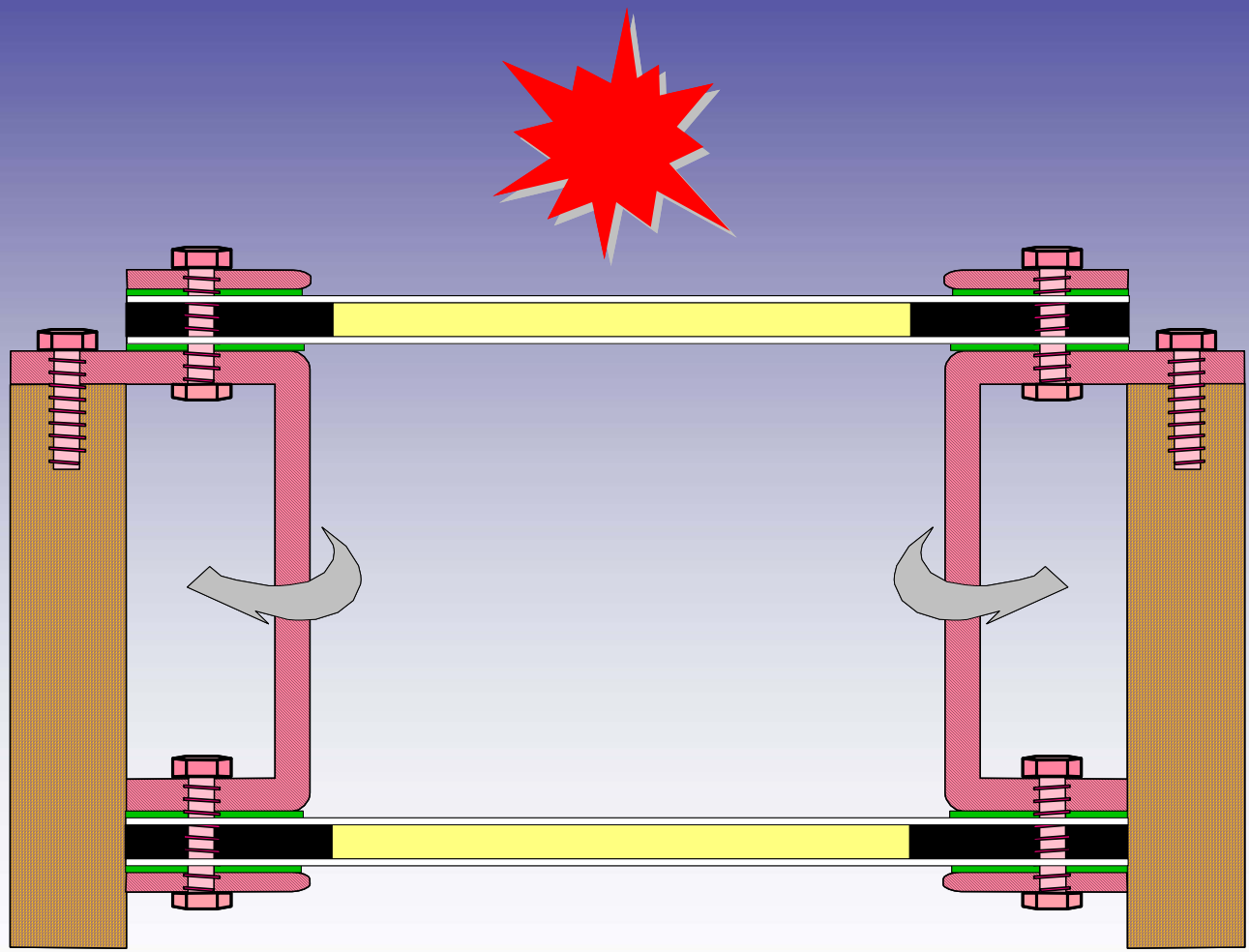
Posttest Photo of Blast Side

# 2nd Generation Design 4

Pretest Photo of Blast Side

Posttest Photo of Blast Side

# 2nd Generation Accepted Design



# Perimeter Anchored Laminates Design Approach

- Laminate to exhibit tension membrane:  extend and attach interlayer(s) into the frame rather than the glass
- Anchor system stronger than laminate
- Laminate to withstand blast overpressure

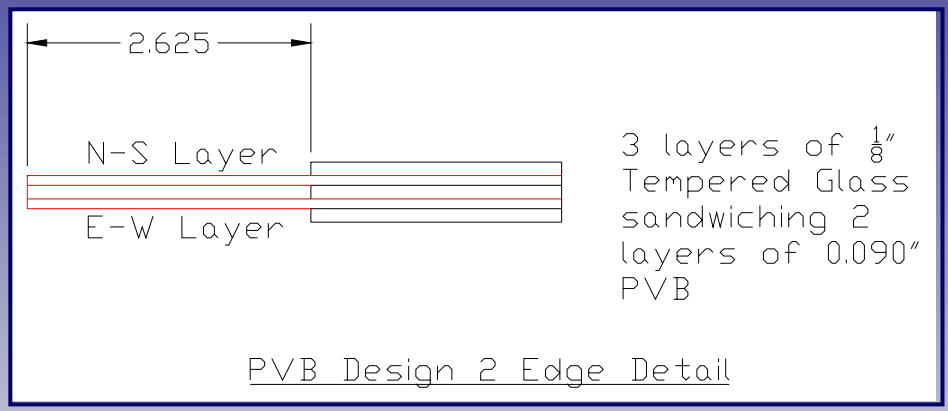
# PAL
# Laminate Types

- Polycarbonate
- PolyVinylButyral (PVB)
- SentryGlas® Plus (SGP)
  - Developed by DuPont
  - Provides greater tear strength and rigidity than PVB

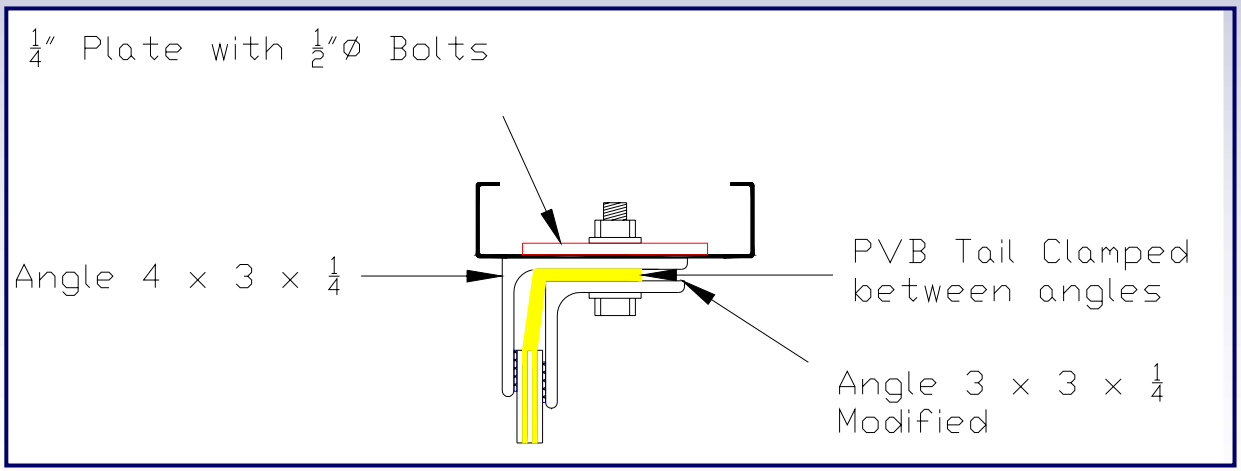
# PAL
# Anchoring Methods

- Clamping
- Mechanical anchoring (i.e. LAMLOK system)
- Bolting
- Modified designs
- Adhesive (not examined)

# PAL Anchoring Methods Clamping




## PVB Laminate "Tails" Clamped in Frame



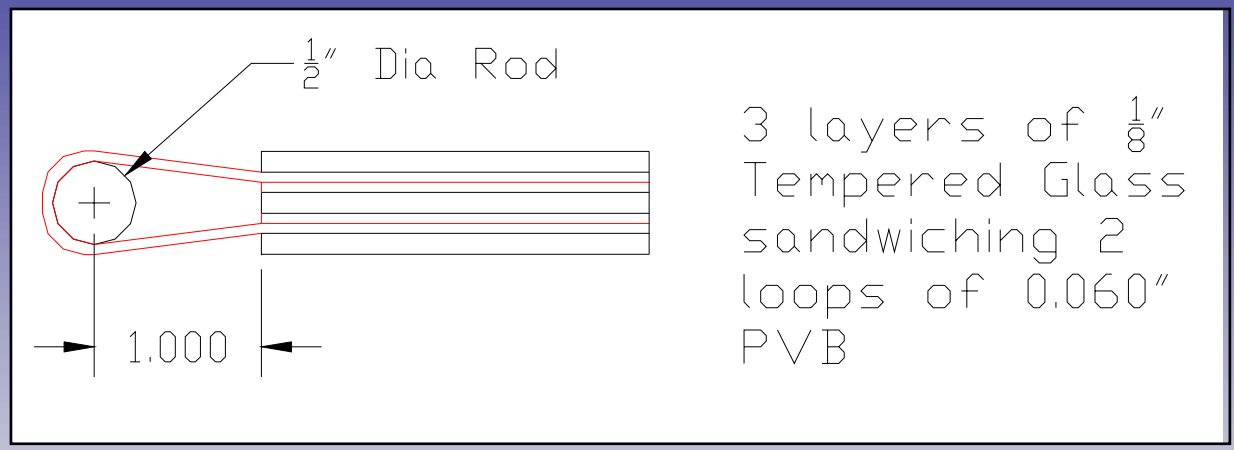
# PAL Anchoring Methods Clamping

Corked Outer Frame

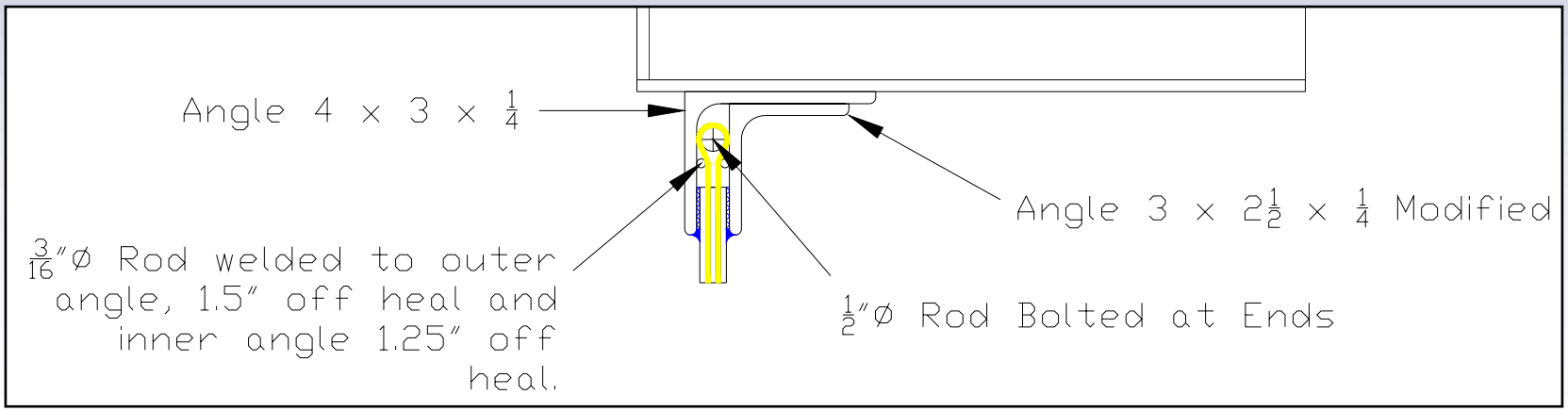
Glazing Before Inner Frame

PVB Tails

# PAL Anchoring Methods
# Mechanical Anchoring




PVB Laminate Wrapped Around Steel Rod and Clamped in Frame



# PAL Anchoring Methods
# Mechanical Anchoring

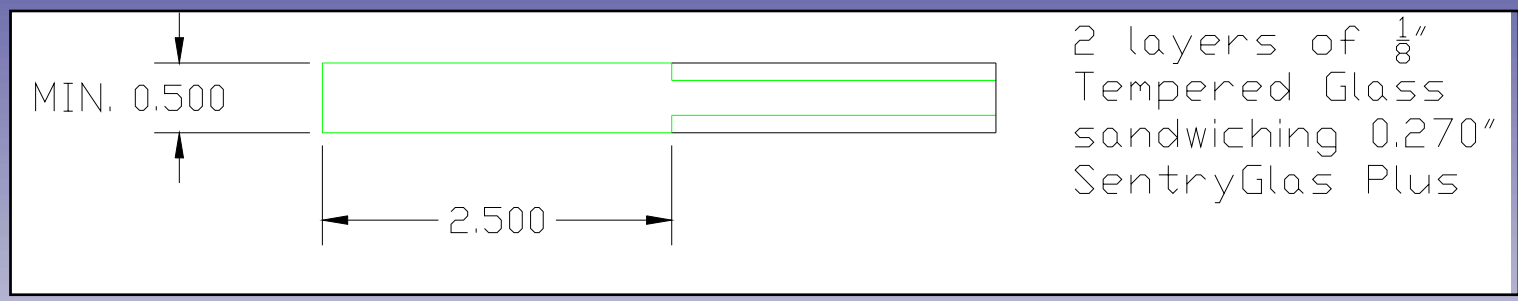

Laminated 1/2” Rods

Rods Welded on Frame

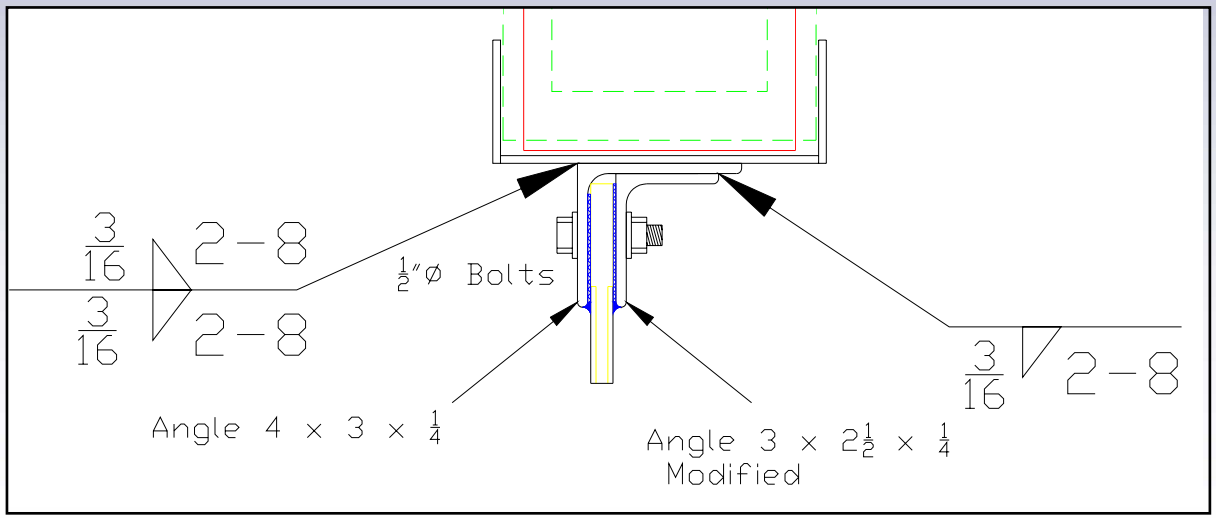
Rod Placement Close-up

Finished Inner Corner

# PAL Anchoring Methods
# Bolting




SentryGlas® Plus Laminate “Tails” Bolted in Frame



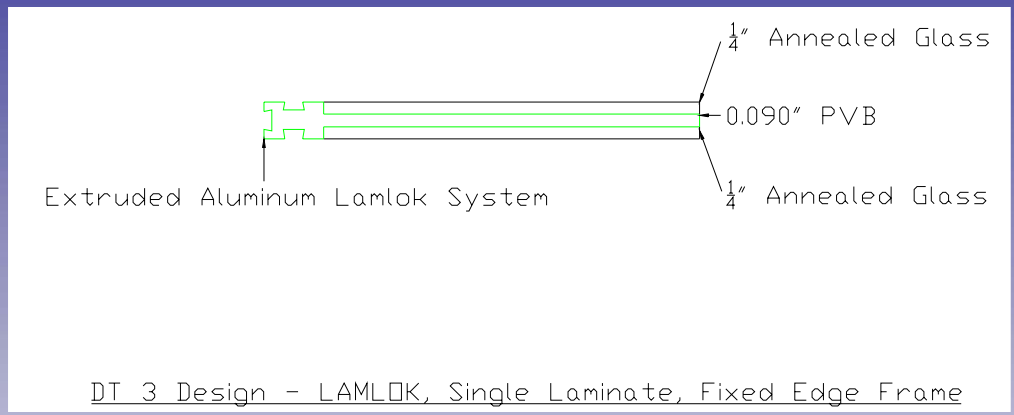
# PAL Anchoring Methods
# Bolting


Outer Frame Detail


Completed Window

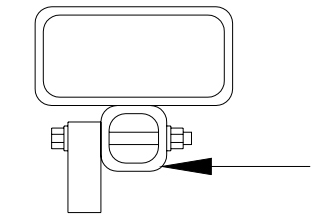
Detail Before Inner Frame

# PAL Anchoring Methods
# LAMLOK




DT 3 Design - LAMLOK, Single Laminate, Fixed Edge Frame

"Lock" and "Key" Mechanism Holds Laminate in Frame




TS 2 x 2 x ¼
Welded 2 @ 8
both sides in
opening.

Steel Frame Section A-A (Typ)

# PAL Full-Scale Testing

Objectives

- Establish proof-of-concept data points for perimeter anchored laminate designs
- Evaluate performance of perimeter anchored laminate designs framed within blast retrofitted walls
- Establish blast resistance data points for various types of laminate windows including bent glass designs
- Validate improved perimeter anchorage methods

# Full-Scale Testing
# Initial Validation


Blast Response of Exterior Walls Experiment 2 (BREW-2)

# BREW 2
# Window Descriptions


**LAMLOK PVB (all 4 sides)**

1/4” AG + 0.090” PVB + 1/4” AG

**Bolted Polycarbonate**

1/8” TG + 0.050” Polyurethane (PT) + 1/4” PC + 0.050” PT + 1/8” TG + 0.008” Film

**Clamped PVB**

1/8” TG + 0.180” PVB + 1/8” TG + 0.180” PVB + 1/8” TG + 0.008” Film

**Hinged LAMLOK PVB**

1/4” AG + 0.270” PVB + 1/4” AG

# BREW 2
# Window Descriptions


**Standard Frame Bite PVB, Bent Glass**

Two panes of 1/4" AG + 0.270" PVB + 1/4" AG

**Bolted SGP**

1/8" TG + 0.270" SGP + 1/8" TG + 0.008" Film

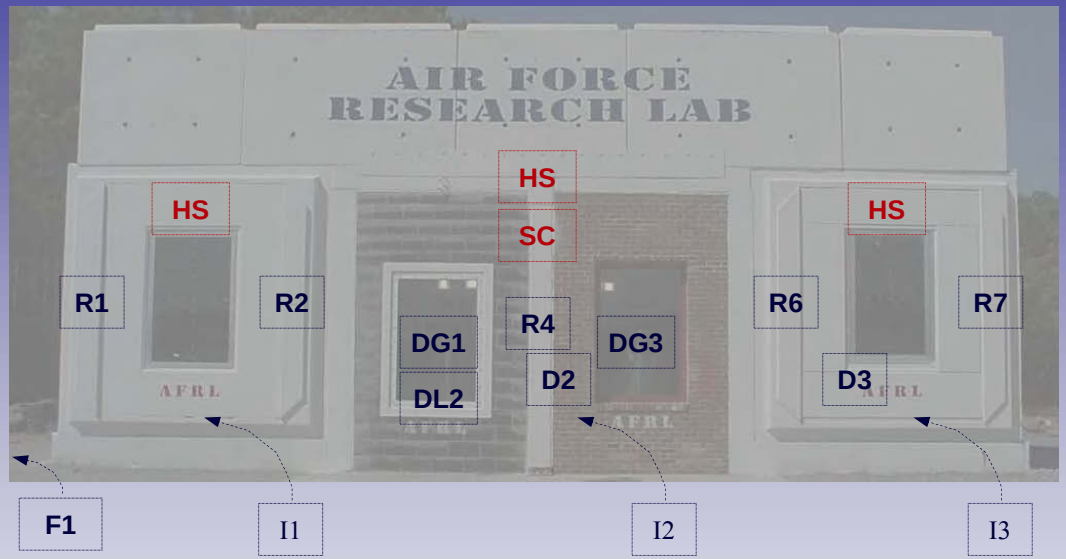
**Mechanically Anchored PVB**

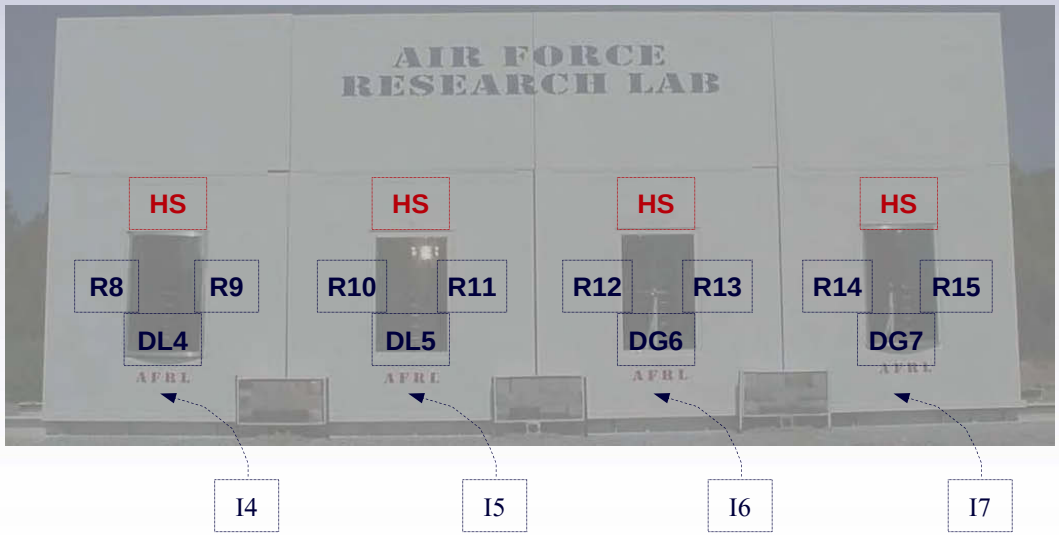
1/8" Tempered Glass (TG) + 0.180" PVB + 1/8" TG + 0.180" PVB + 1/8" TG + 0.008" Film

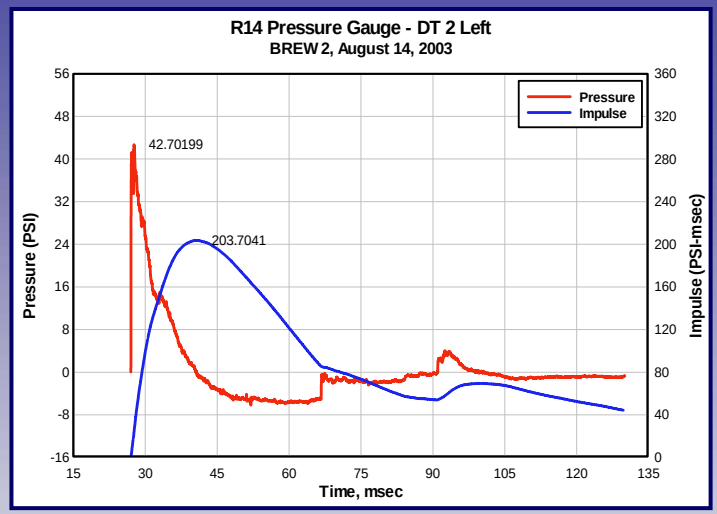
**LAMLOK PVB, Bent Glass**

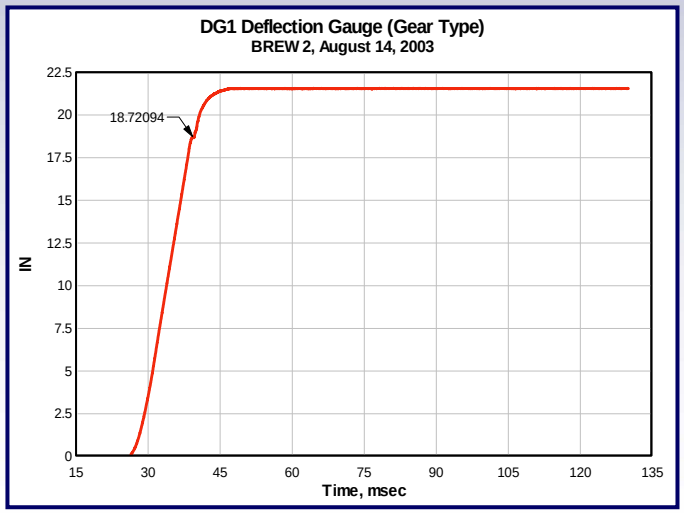
1/4" AG + 0.270" PVB + 1/4" AG

# BREW 2
# Data Collection



# BREW 2
# Test Results

**SUCCESSFUL**


**Mechanically Anchored PVB**

**SUCCESSFUL**


**Clamped PVB**

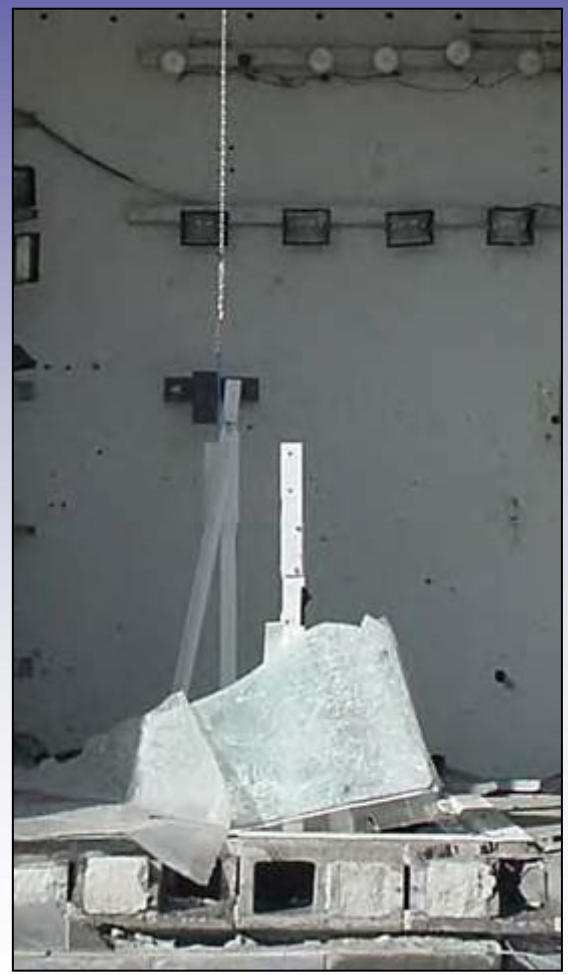
# BREW 2
# Test Results

**UNSUCCESSFUL**



**Bolted SGP**

**SUCCESSFUL**



**Bolted Polycarbonate**

# BREW 2
# Test Results

SUCCESSFUL


SUCCESSFUL


**Standard Frame Bite PVB, Bent Glass**

**LAMLOK PVB, Bent Glass**

# BREW 2
# Test Results

**UNSUCCESSFUL**


**LAMLOK PVB (all 4 sides)**

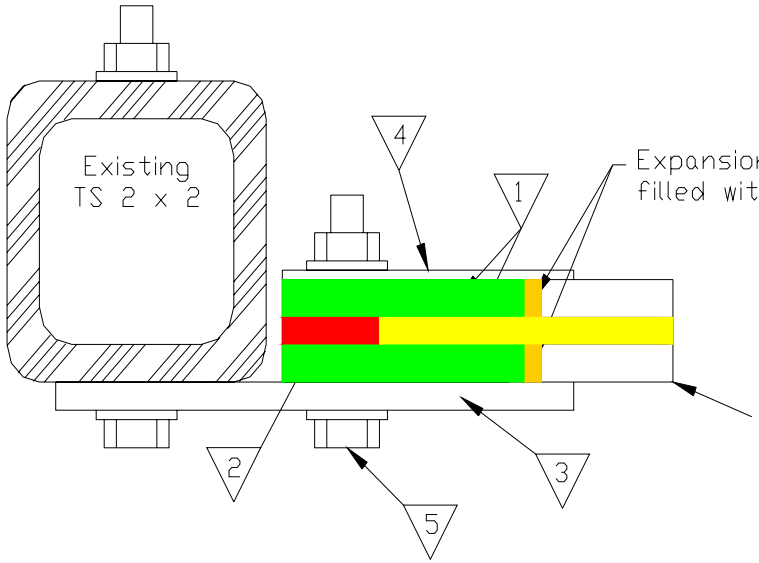
**SUCCESSFUL**


**Hinged LAMLOK PVB**

# BREW 2
# Conclusions

- Mechanical anchorage method effective in allowing laminate to reach maximum tension membrane
- Bent glazing provided higher resistance allowing greater dissipation of energy as indicated by glass shard size/pattern, reduced deflection, and lower glazing velocity
- Anchored, hinged edges demonstrated emergency egress capabilities
- Further research needed for bolting anchorage method

# PAL Anchoring Methods
# Modified Designs




SGP Design 1

| | |
|---|---|
| 1 | $\frac{1}{4}''$ x $1\frac{7}{8}''$ Aluminum flat stock |
| 2 | $\frac{1}{4}''$ x $\frac{3}{4}''$ Aluminum flat stock |
| 3 | $\frac{1}{4}''$ x 4″ Aluminum flat stock |
| 4 | $\frac{1}{16}''$ x $2\frac{1}{4}''$ Aluminum |
| 5 | $\frac{1}{4}''\varnothing$ Grade 5 bolts at 6″ centers |

$\frac{1}{4}$ AG + 0.270″ SGP + $\frac{1}{4}$ AG + 0.008″ film with 1.25″ SGP tail

$\frac{1}{4}$ AG + 0.180″ SGP + $\frac{1}{4}$ AG + 0.008″ film with 1.25″ SGP tail

SGP Laminate Bonded to Aluminum and Bolted in Frame

# PAL Anchoring Methods Modified Designs

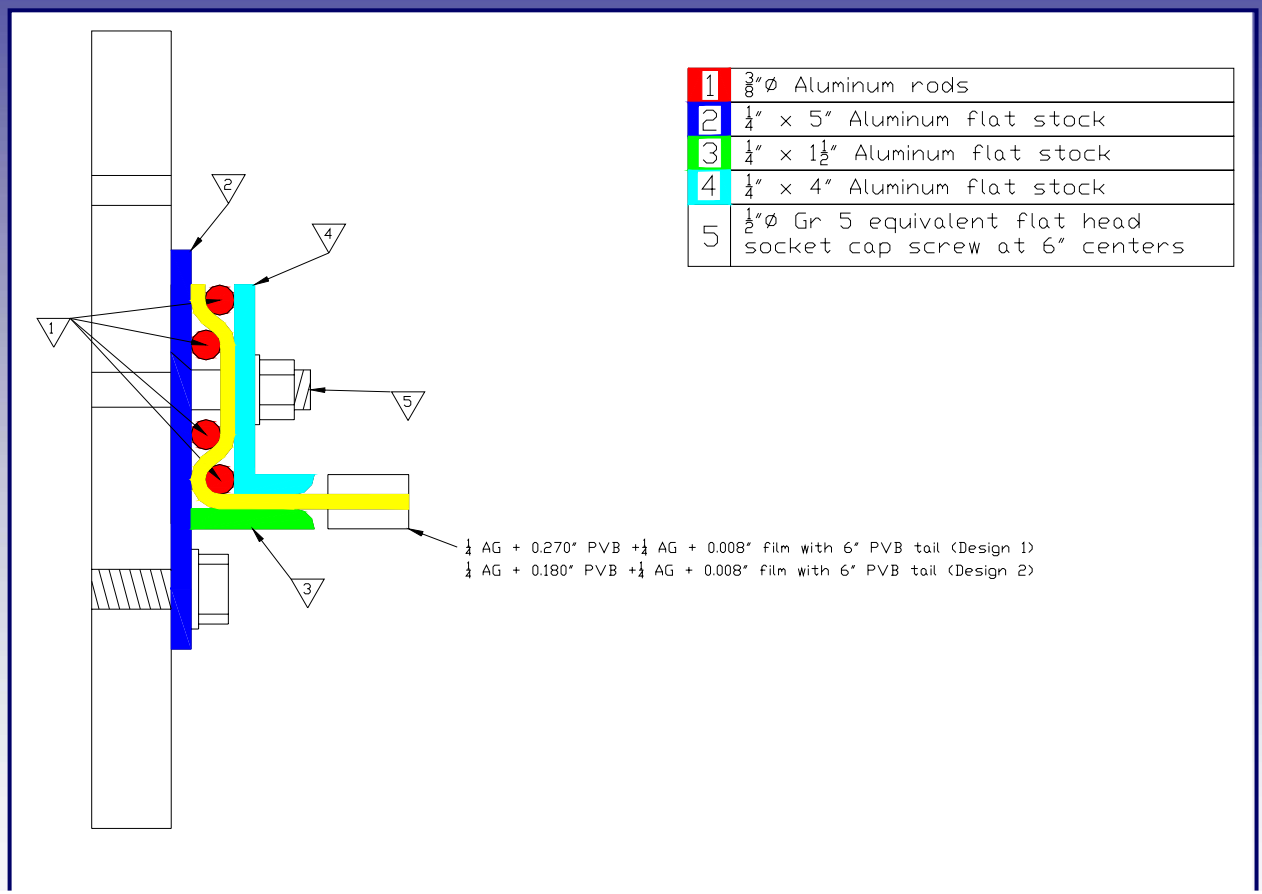
Aluminum Edge Layup

Edge Anchorage Holes

Ready For Vacuum Bag/Autoclave

SGP Laminate Bonded to Aluminum and Bolted in Frame

# PAL Anchoring Methods Modified Designs




PVB Laminate "Tail" Turned 90 Degrees and Clamped in Frame Between Aluminum Rods

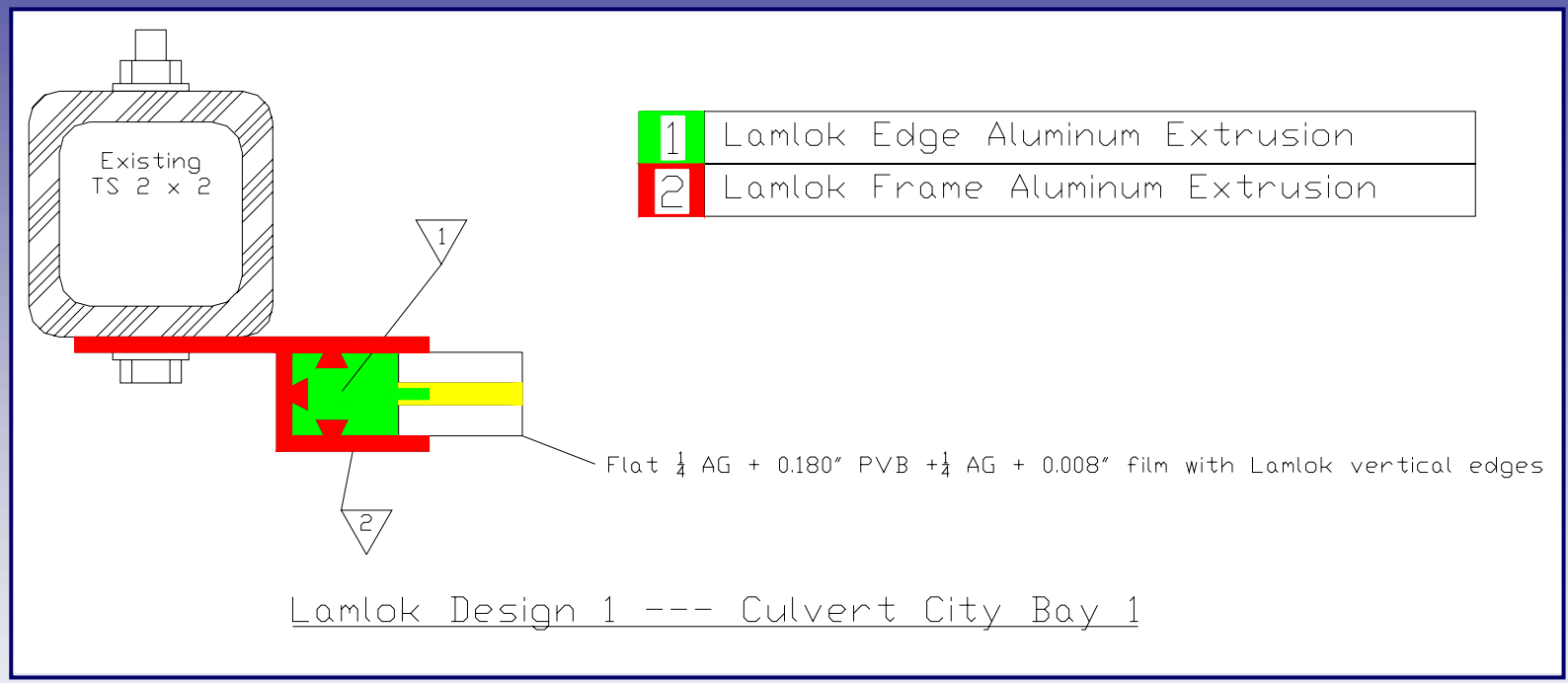
# PAL Anchoring Methods Modified Designs

**Bagged Edges**

**Clamped Corner**

PVB Laminate “Tail” Turned 90 Degrees and Clamped in Frame Between Aluminum Rods

# PAL Anchoring Methods
# Modified Designs




LAMLOK System with Different Interlocking Mechanism

# PAL Anchoring Methods
# Modified Designs

Edge Layup


Bent Frame Pieces

LAMLOK System with Different Interlocking Mechanism

# Full-Scale Testing
# Second Iteration


Blast Response of Exterior Walls Experiment 3 (BREW 3)

# BREW 3
# Window Descriptions


**0.180” SGP Bonded Aluminum + Bolts**

Flat ¼ AG + 0.180 SGP + ¼ AG + 0.008 Film

**0.270” SGP Bonded Aluminum + Bolts**

Flat ¼ AG + 0.270 SGP + ¼ AG + 0.008 Film

# BREW 3
# Window Descriptions

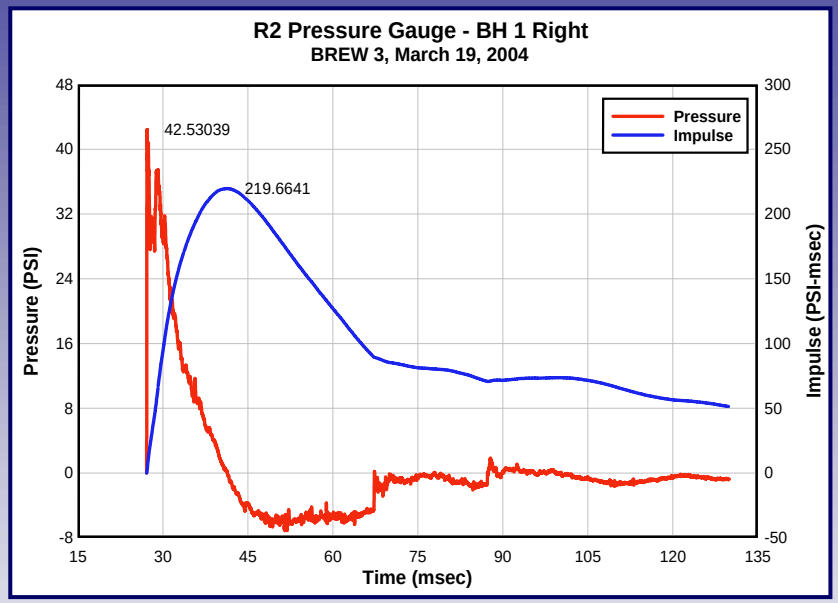

**LAMLOK PVB**
Flat ¼ AG + 0.180 PVB + ¼ AG + 0.008 Film

**0.180” PVB Clamped Tail**
Flat ¼ AG + 0.180 PVB + ¼ AG + 0.008 Film

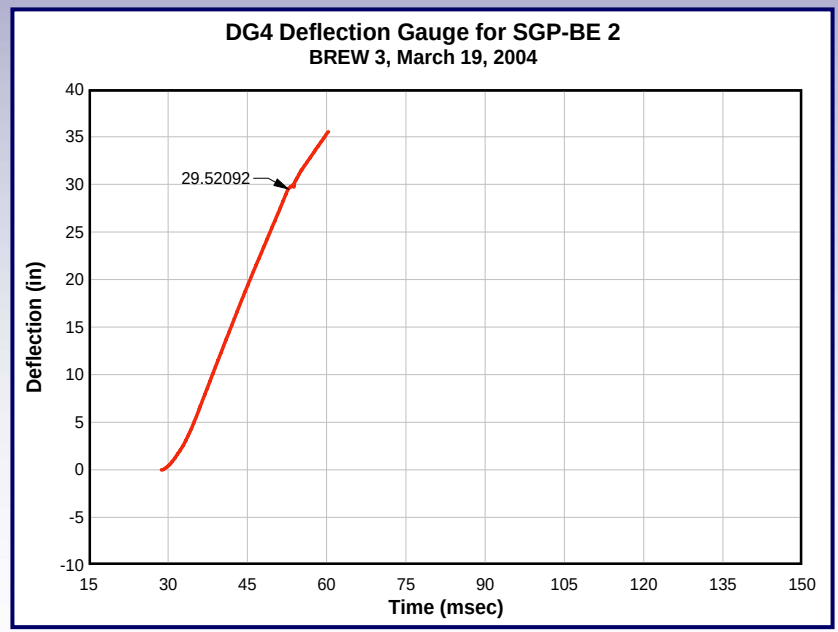
**0.270” PVB Clamped Tail**
Flat ¼ AG + 0.270 PVB + ¼ AG + 0.008 Film

**LAMLOK PVB, Bent Glass**
60” rad. Bent ¼ AG + 0.180 PVB + ¼ AG + 0.008 Film

# BREW 3
# Data Collection




**Deflection Readings Higher**



# BREW 3
# Test Results

**0.180” SGP Bonded Aluminum + Bolts**
**SUCCESSFUL**


**Prevented lethal fragments but portions of the edge bond failed**

**0.270” SGP Bonded Aluminum + Bolts**
**SUCCESSFUL**


**Prevented lethal fragments with no tears or edge bond failures**

# BREW 3
# Test Results

**0.180” PVB Clamped Tail**
**SUCCESSFUL**


**Prevented lethal fragments while tearing along a vertical edge**

**0.270” PVB Clamped Tail**
**SUCCESSFUL**


**Prevented lethal fragments without tearing**

# BREW 3
# Test Results

**LAMLOK PVB**
**SUCCESSFUL**


**Prevented lethal fragments while tearing along both vertical edges**

**LAMLOK PVB, Bent Glass**
**SUCCESSFUL**


**Prevented lethal fragments but an inadequate frame failed**

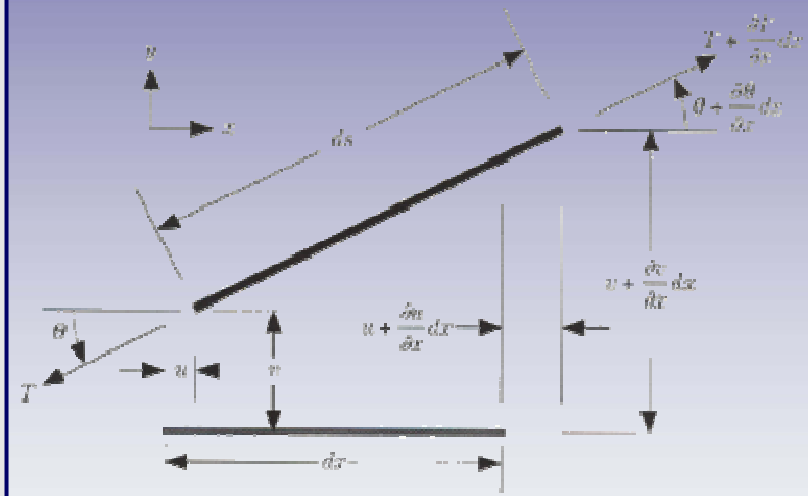
# BREW 3
# Conclusions

- Anchoring PVB using 90 degree clamping method with bolts is an effective low cost option
- Key “tearing/stays in frame” data point established for 180 mil thick PVB
- Window deflection minimally affected by laminate type or thickness
- Additional investigation needed to eliminate bolt shear and edge bond failures

# Modeling & Material Testing

## ANALYTICAL APPROACH FOR LAMINATES

- Develop constitutive equations for the laminates at high strain rates
- Develop non-linear dynamic response model for PAL to airblast loads
- Validate models with experimental test data (loading functions on windows)
- Use models to predict/optimize material parameters for concept design



# Material Testing

## MTS-810 High Strain Rate Testing Machine


- One of few in the country
- Examine high strain rate of laminates (none available in literature)
- 15-400 in/s sample rate velocity
- Supporting polymer working group in testing high density, glass-filled composites for SAE (Society of Automotive Eng.)
- Supporting GERC (Graduate Eng. Research Center) testing PET films

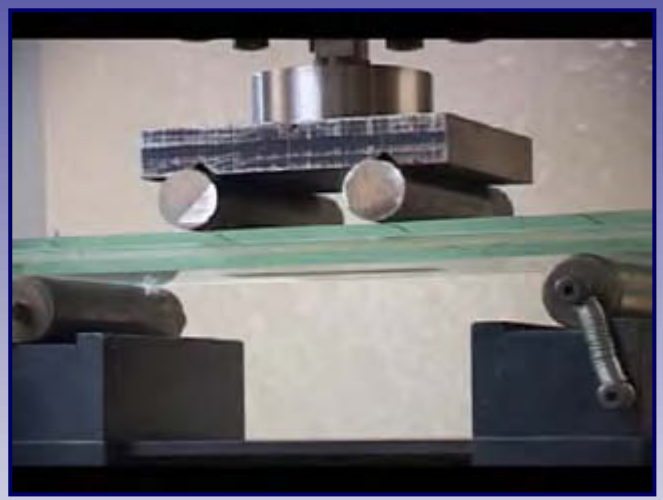
# Material Testing Samples

PVB/Annealed Glass Interlayer


SGP Laminate Bonded to Aluminum

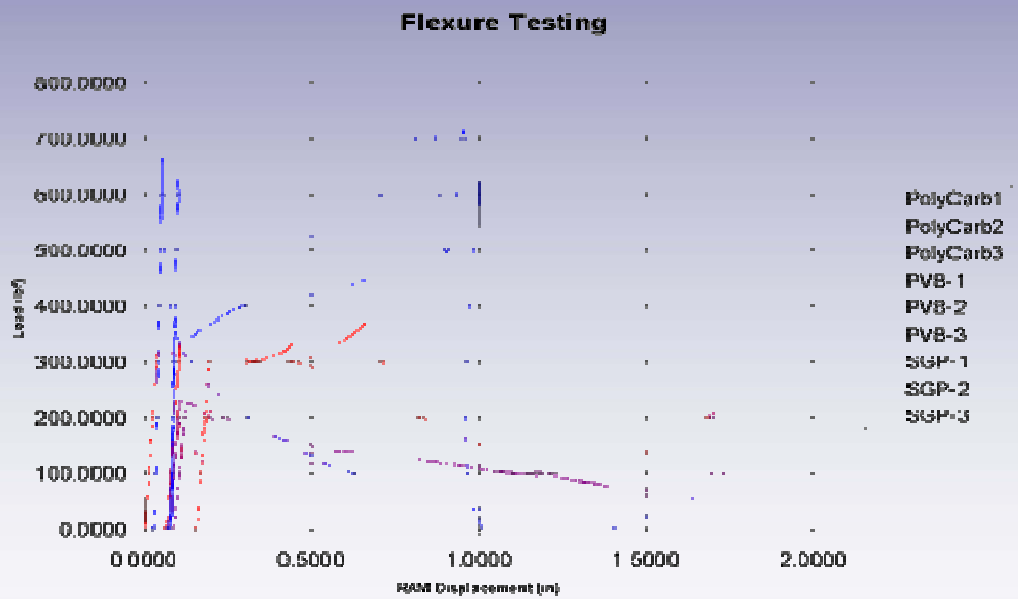
LAMLOK PVB Interlayer System

# Material Testing



SGP Flexural Bend Test

Testing Results



# Future Goals

- Improve the modeling of these systems by developing suitable constitutive models for the laminates to use in finite element codes
- Further characterize stress/strain and high strain rate behavior of window laminates to incorporate into finite element models and engineer level analytical tools
- Improve methods for inclusion of window concepts into wall/window blast protection systems
- Continue to adapt emerging materials for use in force protection

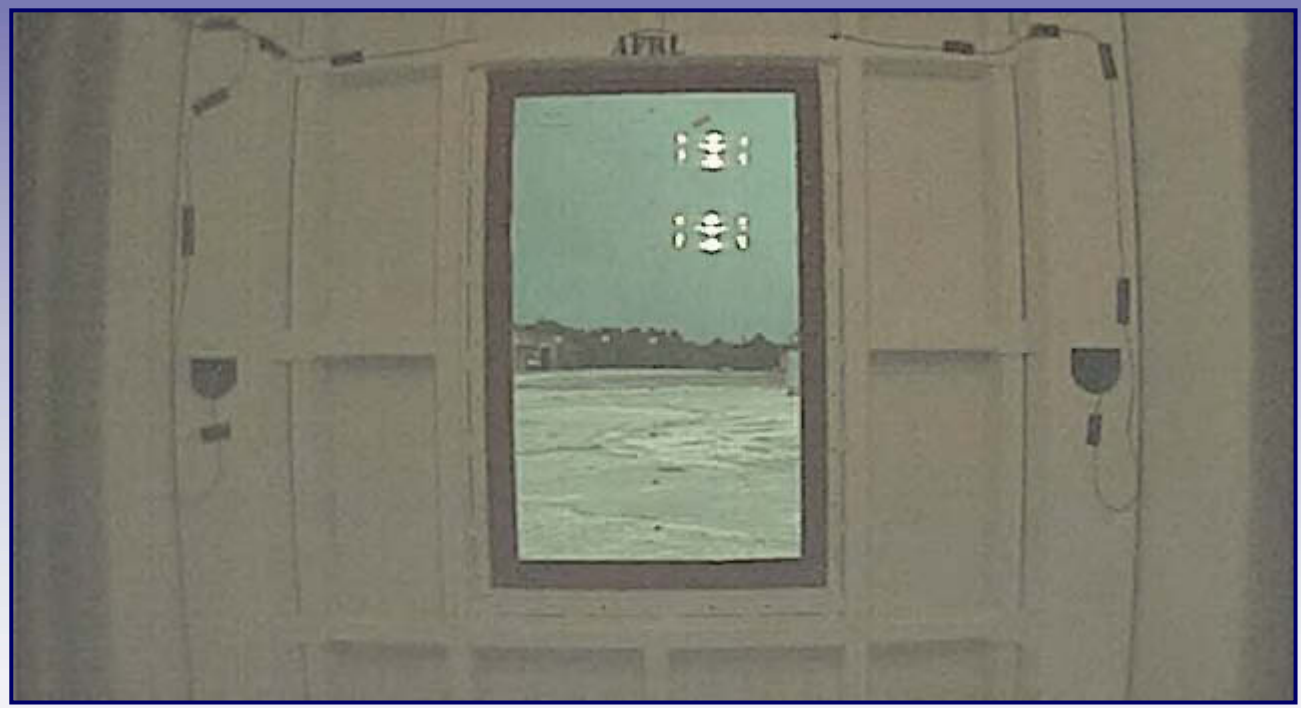
# Summary

- Current design of blast resistant windows
- Development of AFRL blast resistant windows
- Design approach
- Full-scale experiments
- Material testing
- Modeling
- Future goals

# Questions?

# Bolted SGP
# High Speed Video

# Hinged LAMLOK PVB High Speed Video



# SGP Bonded Aluminum + Bolts High Speed Video